Plate 3: Map Showing Bedrock Geology, Topography of the Bedrock Surface, and Areas of Bedrock Outcrop in the City of Alexandria, Virginia and Vicinity – Expanded Explanation

By Anthony H. Fleming, 2015

Introduction

Crystalline bedrock of early *Paleozoic* age is present below the entire city, but crops out only in Holmes Run Valley and tributary ravines in the far western section, and in adjacent parts of Fairfax County, where it has been exposed by erosion along the modern *Fall Zone*. Elsewhere in the map area, the bedrock is buried beneath the eastward-thickening wedge of *Coastal Plain* sediments, and ranges from a few feet to several hundred feet below the modern land surface. **Plate 3** depicts three main features of the bedrock: the geology and structure of the different rock units at the bedrock surface; the elevation and topography of the buried bedrock surface; and areas where the *Piedmont* bedrock and/or its residual soil are present at or very near the modern land surface.

Significance of the Bedrock Surface

The horizon represented by the *bedrock surface* marks a profound hiatus in the geologic record, referred to as an *angular unconformity* (fig. 3-1), during which some 300+ million years (ma) of geologic time is unaccounted for in the local record between the deposition of the early *Cretaceous* *Potomac Formation* and the early *Ordovician* *Taconic orogeny*, when the local bedrock originated. "Angular" unconformity refers to the fact that the bedrock was folded, metamorphosed, and eroded to a surface of low relief before the deposition of the overlying Potomac Formation. In contrast, other than being gently tilted to the southeast and locally affected by faulting, the Potomac Formation is essentially undeformed.

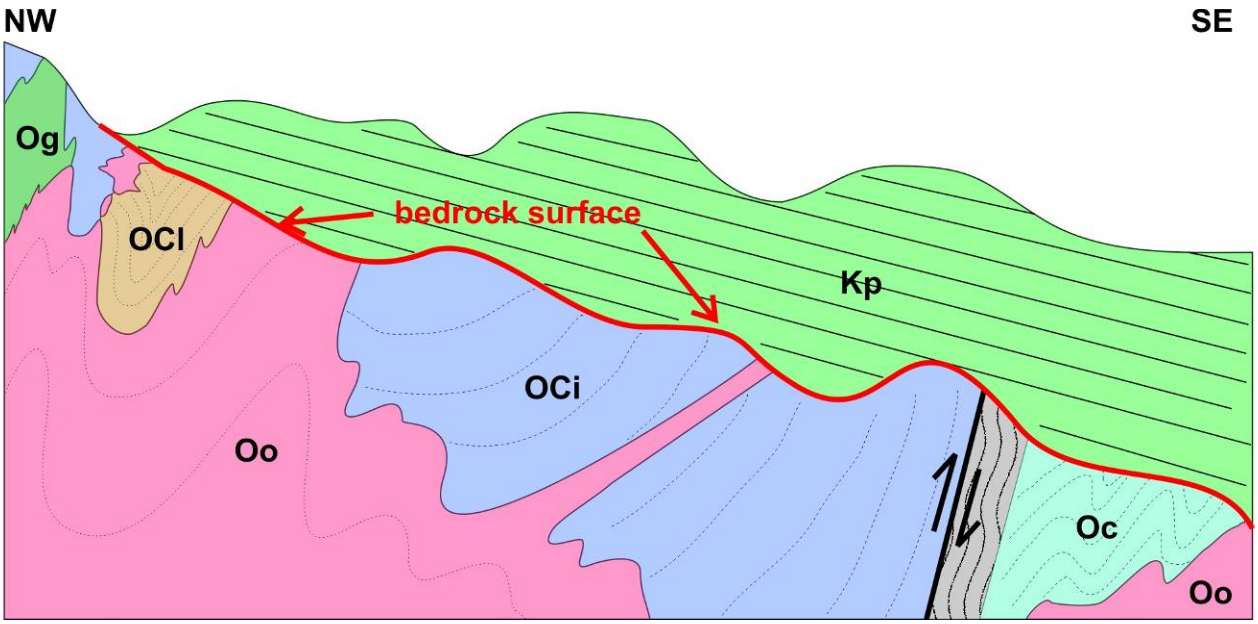

Figure 3-1. Schematic diagram illustrating the angular unconformity represented by the bedrock surface beneath the map area. The Piedmont bedrock (represented by units OCi, OCl, Oc, Og, Oo) was complexly folded, faulted, metamorphosed, and raised into a large mountain range before being beveled by erosion to a low-relief surface. The overlying Potomac Formation (Kp) was deposited along the erosion surface and, other than being gently tilted to the southeast and locally faulted, is essentially undeformed. Note also that the unconformity represents a hiatus of more than 300 million years in the local geologic record, between the Ordovician bedrock (circa 460-475 ma) and the overlying Cretaceous strata (circa 130 ma). Not to scale.

A basic understanding of the *topography* of the bedrock surface is crucial to deciphering several aspects of the subsurface geology of Alexandria, particularly the details of the overlying Potomac Formation. In addition to being an ancient erosion surface, the bedrock surface also represents the altitude of the base of the Potomac Formation, and its topography preserves the basic configuration of the lower Cretaceous depositional basin in which the Potomac sediments accumulated. Valleys on the bedrock surface, for example, suggest riverine channels where major bodies of sand were deposited and may have substantial lateral and vertical extent. On the other hand, the summits of bedrock hills and ridges and the lees behind them may be places where finer sands and muddy sediments accumulated, while some of the broader "flats" on the bedrock surface suggest swampy floodplains and meandering river valleys where a more varied sediment assemblage was deposited. Further, knowledge of the bedrock surface configuration allows reliable estimates to be made of the total thickness of the Potomac Formation, which in turn enables down-dip reconstruction of the different sedimentary *facies* that comprise its various intervals. The bedrock surface also is a significant horizon for several modern environmental processes and issues. In the western part of the map area where bedrock is close to modern base level, the bedrock surface may locally act as a *confining unit* whose elevation determines the locations of springs, seeps, and other points of ground-water discharge from the sandy basal Potomac aquifer, which in turn constitute the primary source of base flow for numerous streams and wetlands. Likewise, the bedrock surface and the *tectonic* structures it contains are crucially important for recognizing and evaluating young faults and the potential seismic risk they pose. Finally, the historical geology of the early Paleozoic bedrock is a fascinating story in its own right, and the rocks exposed in the western part of the city reveal a wide variety of features of great educational, ecological, and scientific value.

Previous Studies

The bedrock topography and geology of the entire City of Alexandria have not previously been mapped and published at a detailed (1:24,000 or larger) scale, though parts of the city were vicariously included in a broader mapping effort by the U.S. Geological Survey in the 1970's and 1980's focusing on Fairfax County. As a part of that effort, **Drake and Froelich (1986)** mapped the geology of the Annandale Quadrangle, which encompasses the far western sections of the city, while **Daniels (1980)** interpreted the bedrock geology beneath the Coastal Plain of Fairfax County, Arlington, and Alexandria using geophysical data. **Froelich (1985)** included a small-scale map showing the inferred extent and altitude of the base of the Potomac Formation (the bedrock surface); the map shows relatively few data points in the city, relative to adjacent areas in Fairfax County. **Huffman (1975)** included the city in a bedrock geology map of northern Virginia inside the Capital Beltway. Prior to that, **Darton (1950)** described several wells and made a number of observations concerning the bedrock surface in the vicinity of Seminary Ridge, while **Johnston (1964)** field located, mapped, and obtained descriptions of known water wells throughout the region. The city was also included in the very first geologic map ever made of the Washington, D.C. area, by **Keith and Darton in 1901**. Plate 3 combines new information collected during the present study with the observations and interpretations from these earlier efforts into a unified interpretation of the bedrock beneath the city and adjacent areas.

Data Sources, Uses, and Methods

All of the aforementioned reports served as sources of data for the present study; these were supplemented by the collection of geotechnical borings obtained from the city and VDOT, and by numerous observations of the bedrock and basal beds of the Potomac Formation in natural outcrops and excavations throughout the western part of the city. The locations of all of the various data used for all aspects of this study are given on **Plate 1: Map Showing the Distribution and Sources of Geological Data Available for the City of Alexandria, and Vicinity**, and the details are described in the "**Plate 1-Expanded Explanation**" and in several associated databases. The following section provides a brief review of the types and sources of data used specifically to construct plate 3; the locations of specific outcrop, well, and borehole data used to determine the elevation of the bedrock surface are also shown on plate 3.

Natural outcrops were useful in the far western part of the city, where bedrock is exposed or close to the modern land surface. In addition to numerous outcrops showing the lithology and structure of the bedrock itself, the base of the Potomac Formation and its contact with the underlying bedrock were directly observed or could be reliably inferred at several locations along the valley walls of Holmes and Four Mile Runs and their major tributaries. The contact is well exposed in ravines in Dora Kelley and Rynex Natural Areas in western Alexandria, as well as in Barcroft and Glencarlyn Parks (fig. 3-2) in southern Arlington County, where it is typically marked by a line of seeps and springs caused by abundant discharge of ground water from the sandy units that comprise the base of the Potomac Formation. Work done previously by the author (**Fleming, 2005**) at Green Spring Garden Park in nearby Turkeycock Valley also provided insights concerning local bedrock topography and the location of a significant buried bedrock valley in that area.

Figure 3-2. Outcrop exposing the unconformity between dark gray Piedmont bedrock at stream level (represented here by the Lake Barcroft Metasandstone) and overlying gravelly sand of the Potomac Formation. The undulating nature of the contact indicates erosion and channeling by early Cretaceous streams. The unconformity truncates the bedding schistosity in the underlying bedrock, which dips to the right at about 45 degrees. Glencarlyn Park, Arlington County. Photo by Tony Fleming.

The records of dozens of wells and boreholes figured prominently in the interpretation of the elevation and configuration of the bedrock surface, especially in the Coastal Plain section of the city where bedrock is not exposed. The single largest set of subsurface data in the city is from Johnston (**1961**, **1964**), who documented the locations and characteristics of 80 historical water wells in and adjacent to the city, many of them fairly deep. Although only 5 of the wells have **formation logs** describing the sequence of geologic materials encountered during well construction, all of them are summarized by total depth, casing length, aquifer they are developed in, and other features that can be useful, though not necessarily definitive, for inferring the elevation of the bedrock surface. For example, large wells were commonly developed in the thick water-bearing sands at the base of the Potomac Formation, and it was a common practice to "seat" the well casing on or just into the bedrock surface. In this situation, the casing length or well depth given by **Johnston (1961)** can often act as a proxy for depth to bedrock (figure 3-3).

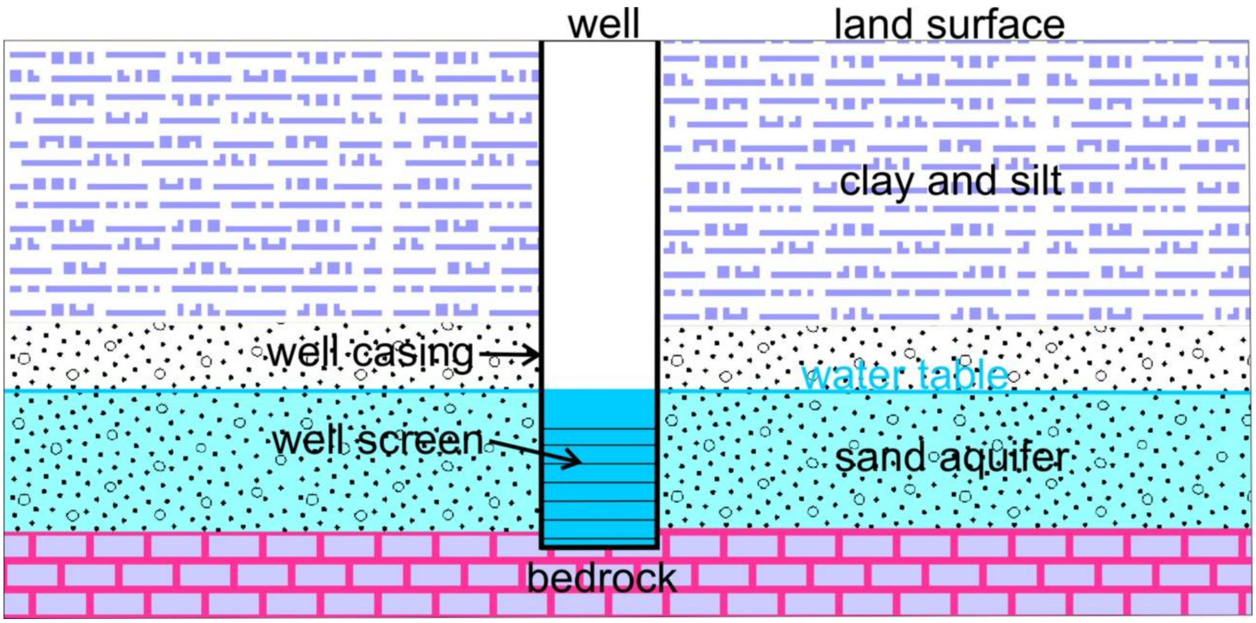

Figure 3-3. Schematic diagram showing typical construction of a water well developed in the basal sandy beds of the Potomac Formation. In such installations, the well casing (usually steel) is commonly seated on or just into the bedrock, thus the total well depth is often a good indicator of the depth to the bedrock surface.

Darton (1950) documented the locations of 30 wells in and near the map area. A few of these reached bedrock, and thus provide a firm altitude of the bedrock surface. Most wells did not reach bedrock, however, but are nevertheless important because they indicate the minimum depth (maximum elevation) of the bedrock surface. **Froelich's (1985)** maps also show 12 unique boreholes in the map area, and another 17 boreholes in the surrounding area, that give the altitude of the base of the Potomac Formation.

<u>Geotechnical borings</u> were obtained from the city and VDOT for more than 190 building sites, highway interchanges, schools, and other infrastructure projects. The bedrock surface was encountered at only a few of the geotechnical boring sites, but relatively deep borings that did not reach bedrock at other places were useful for constraining the maximum elevation of the bedrock surface at these sites.

Information on the geology and altitude of the bedrock surface from all of these sources of data is shown on plate 3. These data were used to interpret bedrock topography and generate the bedrock structure contours that appear on plate 3. The density and quality of data were judged to be sufficient to support the use of a 50-foot contour interval, particularly in the western part of the map area where the bedrock surface is exposed or proximal to the surface. The bedrock topography contours are relative to a datum of mean sea level.

Aeromagnetic maps (figure 3-4) of the Alexandria and Annandale 7.5-minute quadrangles allow the bedrock geology to be interpreted beneath the Coastal Plain with reasonable confidence, despite a lack of exposure. The *aeromagnetic* signature is almost entirely the result of the magnetic properties of the bedrock, and is little affected by the overlying Coastal Plain deposits (**Daniels, 1980**). Consequently, by comparing the aeromagnetic anomalies of known rock units and structures exposed in adjacent parts of the Piedmont, and tracing these beneath the Coastal Plain cover, it is feasible to make some first-order approximations of gross bedrock *lithology* and structure. These lithological interpretations are aided by descriptions of the bedrock encountered in a handful of deep wells. Daniels (1980) made such an interpretation for Fairfax County, using both aeromagnetic and gravity data. Much of the geologic interpretation presented herein is based on Daniels' report, and modified by my own knowledge and experience with these rocks, especially in the adjacent Washington West Quadrangle (**Fleming and others, 1994**) just to the north, and in parts of Holmes Run gorge and other nearby stream valleys where bedrock is well exposed.

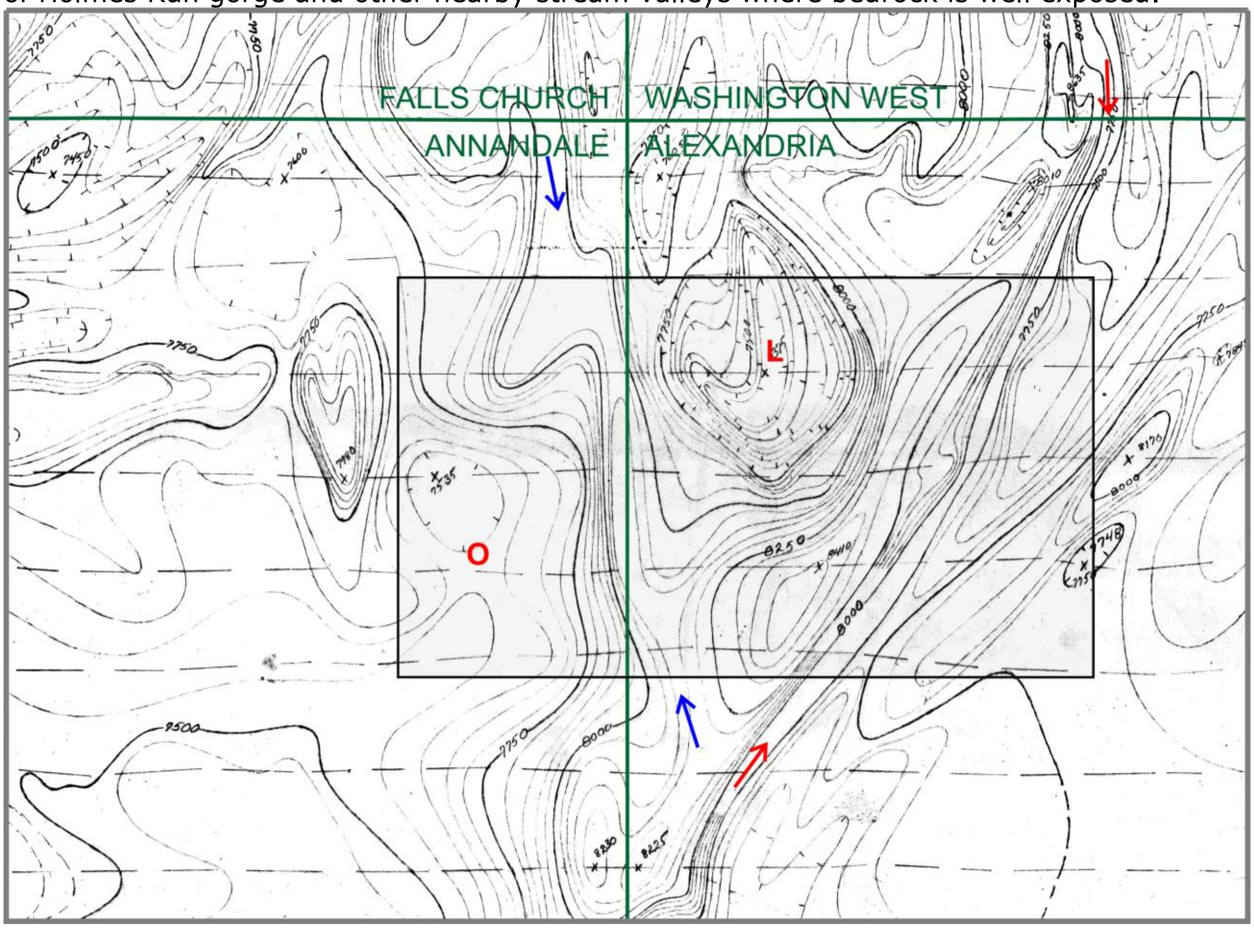

Figure 3-4. Aeromagnetic map of the Alexandria, Annandale, and extreme southern portions of the Falls Church and Washington West 7.5-minute quadrangles. The area covered by the Geologic Atlas of Alexandria is outlined in gray. Some of the more prominent features visible on the map include: the intense magnetic gradient (red arrows) marking the position of the Rock Creek shear zone; a north-northwest-trending lineament (blue arrows), the central segment of which parallels the Indian Run-Occoquon Granite contact, but the rest of it of unknown significance; a pronounced magnetic low (L) beneath the north-central part of the map area, assumed to be caused by a sizable intrusive body; and the flat pattern (O) in the southwest part of the map area associated with the Occoquon Granite batholith. Source: unpublished USGS aeromagnetic map, contour interval 50 nT (gammas).

Bedrock Topography and Configuration of the Base of the Potomac Formation

The overall map pattern indicates a relatively smooth bedrock surface that slopes east-southeast at an average rate of about 100-110 feet per mile across the City, with some local variation in the structural gradient. Most of the apparent dip is attributable to west-to-east tilting of the regional landscape during and after deposition of the Potomac Formation. The relatively smooth appearance of the bedrock topography may be an artifact of the overall thin data density: where bedrock elevation data are more abundant in the western part of the map area (generally corresponding to bedrock surface altitudes at or above sea level), the bedrock surface beneath the Potomac Formation shows noticeably greater local relief, including several shallow, but relatively well defined valleys. On the other hand, data points that reach the bedrock surface are fewer and more widely scattered to the east, resulting in a flatter-looking, more interpolated bedrock surface altitude. It is noteworthy in this context that the bedrock surface shows more local relief at places where subsurface data are concentrated, such as the Piney Court area of Alexandria where **Darton (1950)** presents intriguing well data, and in the Green Spring Garden Park segment of Turkeycock Valley, where a prominent, sand-filled bedrock valley is well defined by outcrop, water well, and hydrogeological data (**Fleming, 2005**). Small scale local relief along the bedrock surface also is suggested by undulations in the elevation of the contact observed in outcrops in Holmes Run Gorge and other stream valleys (c.f., fig. 3-2). Given sufficient data, it seems likely that much more local relief would be apparent on the bedrock surface than is evident from the current data set.

The data indicate the presence of several valleys incised into the bedrock surface to various depths. The largest of these extends westward beneath the south side of Cameron Valley; two or more tributaries appear to converge into the main bedrock valley in the vicinity of South Van Dorn Street. Fingers of this valley system, referred to herein as the "Cameron bedrock valley", appear to extend all the way to the Coastal Plain boundary to the west. A second, somewhat less well-defined valley more or less parallels Four Mile Run before bending west toward the Baileys Crossroads area. Segments of smaller(?) valleys can be identified locally, but their true extent, continuity, and relation to the larger bedrock valleys is not always readily evident from existing data. The Turkeycock Run/Green Spring Garden bedrock valley, for example, which is responsible for the outlier of Potomac Formation that extends west through Pinecrest, appears to continue southeastward below Lincolnia toward Holmes Run, but is increasingly ill defined in that direction. It may cut through the modern valley walls in the heavily urbanized section of Holmes Run between Shirley Highway and Beauregard Street, or it may continue southeast in the direction of Backlick Run, as it is currently depicted on **plate 3**. Which of these alternatives is correct is ultimately a matter of speculation given the absence of definitive data in either area.

As the Potomac Formation began being deposited in the early Cretaceous, bedrock valleys would have served as locations of relatively high-energy river channels, hence coarse-grained channel fills of considerable longitudinal extent might reasonably be expected to be found along and near the *thalwegs* of the valleys (fig. 3-5). Some of these large channels may have persisted through time in the same locations as the Potomac depositional basin evolved: major trunk streams that occupied the valleys could have produced and perpetuated broad, alluvial lowlands in the early Cretaceous landscape, in which stream flow remained concentrated. This relationship is clearly the case for the Cameron bedrock valley, where a stack of major sand bodies extending well into the upper intervals of the Potomac Formation is documented by **Froelich (1985)**. The situation appears similar but less well-defined along the Four Mile Run bedrock valley, where large sand bodies up to 100 feet thick crop out above the bedrock surface along the modern valley walls. The bodies of sand that crop out along lower Holmes Run may also be localized within a bedrock valley. However, this relationship is by no means universal, and it seems likely that bedrock valleys became less significant in determining the distribution of river channels and other sedimentary facies higher in the Potomac Formation, as the bedrock surface became increasingly deeply buried by Potomac sediments and thus progressively more isolated from the early Cretaceous alluvial landscape.

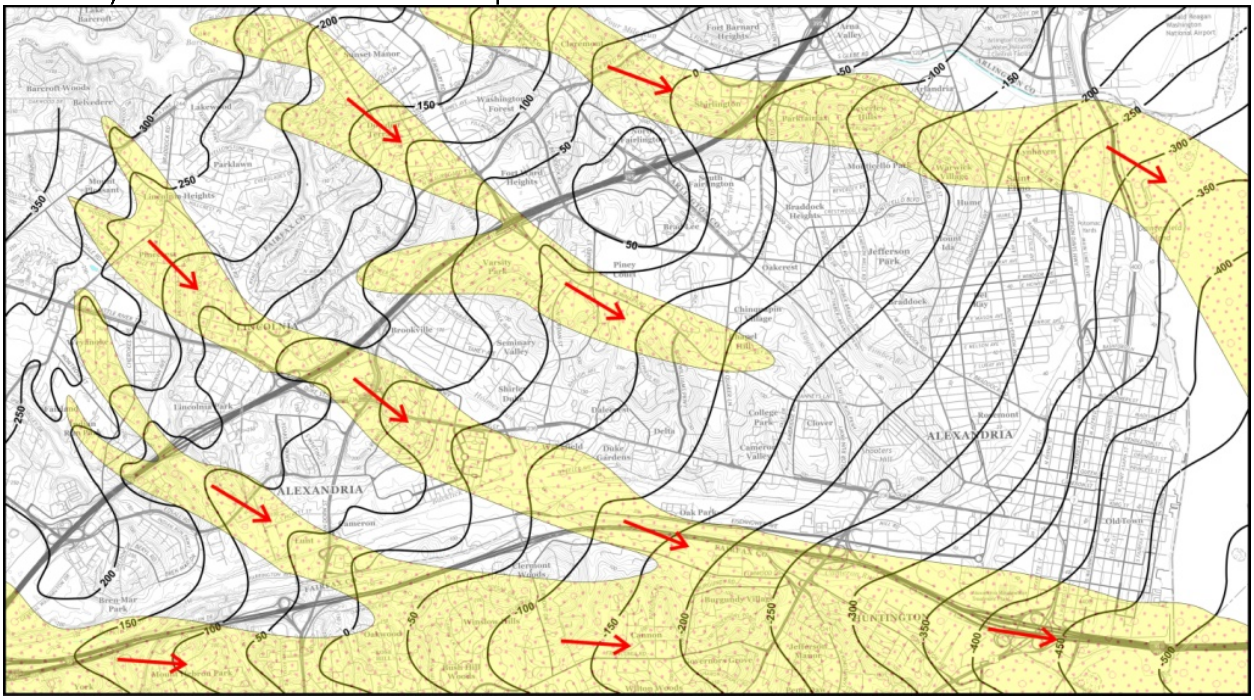

Figure 3-5. Conceptual diagram illustrating the relationship of thick, longitudinally extensive bodies of sand (pattern) at the base of the Potomac Formation to major bedrock valleys.

Bedrock Geology of Holmes Run Gorge and Vicinity

The bedrock exposed in the western part of the map area consists of *metamorphosed* sedimentary rocks intruded by early Ordovician *plutons* of *gabbro*, *tonalite*, and *granite*. The rocks that now underlie Alexandria may not have originally been part of North America or, at the very least, were tectonically transported long distances from their places of origin. Most, and perhaps all of them, formed in and below a *subduction zone* broadly referred to as the Taconic Arc, which lay somewhere to the east of the North American continent very early in the Paleozoic. The subduction zone formed at a plate boundary where the crust of an ancient ocean was being subducted beneath an island arc slowly moving westward towards North America; a reasonable analogue might be the Indonesian archipelago, which lies between the Eurasian and Australian continental plates and is slowly but surely being swept up as the two larger plates gradually converge. The bedrock below Alexandria consists of at least two tectonically distinct *terranes*—the Potomac terrane, which includes the rocks exposed in the western part of the City, and the Chopowamsic terrane, a group of volcanic arc rocks that underlie Old Town—which arrived when the Taconic Arc eventually collided with and was accreted to North America during the Paleozoic. Subsequent to their accretion, these terranes and their boundaries were further rearranged by major *strike-slip faulting* that accompanied the collision of the North American continent with *Gondwanaland* to form the supercontinent of *Pangaea* during the latter half of the Paleozoic Era.

Indian Run Formation: The principal metasedimentary rock unit exposed in the city is the Indian Run Formation (**Drake, 1985**), a metamorphosed *diamictite* containing scattered elliptical lumps of quartz, small "wafers" of mica schist, and sausage-shaped clasts of light-colored feldspathic rock floating in a massive, *quartzofeldspathic* matrix. At some places along Holmes Run, the rock contains few megascopic inclusions and consists mostly of a massive quartzofeldspathic matrix. Elsewhere, however, the rock contains larger slabs and fragments of metamorphosed sandstone, schist, volcanic rocks, soapstone, and other exotic rocks. The sandstone and schist fragments closely resemble the Lake Barcroft Metasandstone and Accotink Schist of the Annandale Group, described below.

Figure 3-6. Indian Run Formation along Holmes Run. Top: Typical diamictite, with scattered lumps of gray quartz, dark "wafers" of mica schist, and a large, sausage shaped clast of fine-grained feldspathic rock below coin (coin is 2.5 cm wide), scattered in a gray, fine-to medium grained matrix. Bottom: Chaotic-looking rock choked with a variety of clasts, the most prominent being large rounded masses of dark, fine-grained amphibolite that may be metamorphosed volcanic rocks. The rock in this photo resembles intrusive rock with many xenoliths. Outcrop is about 8 feet across. Photos by Tony Fleming.

The medium-grained matrix consists chiefly of quartz, *plagioclase*, and mica and ranges from massive to strongly *foliated*. The rock appears to have been metamorphosed to garnet grade, as small red garnets are a common constituent. The Indian Run Formation lacks stratification in any usual sense of the word, and appears rather massive in most exposures.

The less foliated parts of the matrix vaguely resemble granite, and outcrops containing large numbers of *clasts* (e.g., figure 3-6) are sometimes difficult to distinguish from intrusive rocks with many *xenoliths* of wallrock.

Most of the rock exposed in Holmes Run Gorge is clast poor, containing only scattered quartz pebbles and small schist chips. Good examples of diamictite containing abundant large fragments of exotic rock can be seen in a large, rounded outcrop near the west bank of Holmes Run, about 500 feet upstream of the City limits (figure 3-6), and in southern Arlington County along Four Mile Run in Glencarlyn Park, where it contains large slabs of sandstone and schist up to 20 feet in length, as well as other exotic fragments. The rock exposed in the bed of Holmes Run downstream from Shirley Highway also contains abundant inclusions, but this section of the streambed is frequently obscured by modern alluvium. The Indian Run Formation is similar to the Laurel Formation in Rock Creek Park (DC) and adjacent parts of Maryland (**Fleming and others, 1994**; **Fleming and Drake, 1998**), and there is a possibility that the two are the same unit, offset by several miles along the Rock Creek Shear Zone (see the following section on ***Bedrock Geology Beneath the Coastal Plain***).

The origin of the diamictite is equivocal. Several hypotheses have been advanced to explain the peculiar appearance of the Indian Run and its virtually identical counterparts, the Sykesville and Laurel Formations, but the enigmatic character of these rocks has made a definitive conclusion extremely elusive. Up until about the mid 1960's, most geologists thought these rocks were intrusive; in fact, they were originally called "Sykesville Granite" and "granite gneiss" (**Keyes, 1895**; **Keith and Darton, 1901**; **Johnston, 1964**). Several features of these rocks are incompatible with such an origin, however, not least of which are the obvious clasts they contain, including the ubiquitous lumps of quartz, which would not be stable in granite magma. A potentially more enduring hypothesis is submarine sliding of unconsolidated sediments along the sides of a continental slope or submarine trench, as proposed by **Hopson (1964)** in his exhaustive treatment of the Maryland Piedmont. In an updated version of this idea (c.f., **Drake, 1985**; **Drake and Froelich, 1986**), the slumping and sliding were triggered by the arrival of a thrust sheet bearing the exotic rocks (Annandale Group) that are now seen as fragments, or "olistoliths", within the diamictite. In this model, the Annandale Group and Indian Run Formation constitute a "tectonic motif" composed of a sedimentary mélange (Indian Run Formation) and its overlying thrust sheet of schist and metasandstone (Annandale Group). The Sykesville and Mather Gorge Formations were interpreted to have a similar tectonic relationship, forming a second "motif". Subsequent work on the latter two rock units along the Potomac Gorge (**Kunk and others, 2005**) makes the thrust sheet-mélange hypothesis rather implausible, however: the two formations were determined to have been metamorphosed together, but at very different crustal depths, and thus could not have been assembled as envisioned. More recently, **Fleming and Self (2010)** pointed out that portions of the diamictite contain volcanic debris and strongly resemble pyroclastic rocks found in modern volcanic belts. The geochemistry of the rock is a poor match for felsic volcanics, however, and the rock contains detrital *zircons* with a wide age scatter and other features more characteristic of a sedimentary origin in a submarine trench (**Martin and others, 2015**). In any case, whatever origin one might invoke must take into account the following features.

Some of the sediment that makes up the Indian Run Formation is non-marine in origin: rounded quartz pebbles and sand-sized grains of quartz and feldspar are very likely of continental origin and may have been delivered to a submarine trench via large river systems draining a nearby landmass, by tidewater glaciers (some clasts show "flatiron" shapes characteristic of a glacial origin), or some combination. On the other hand, part of the matrix consisted of mud (now metamorphosed to mica, garnet, and fine feldspar) that probably did accumulate in a marine environment, potentially along the sides of the submarine trench. Although its top and bottom are not exposed, the Indian Run appears to be more than 10,000 feet thick, and most of it is remarkably homogeneous. Thus, the different grain-size fractions of the diamictite were thoroughly mixed by the process of deposition: repeated slumping and sliding of unconsolidated sediments along the sides of a steep, seismically active trench appears to be the most plausible explanation, given the vast scale of the formation. It seems likely that many details have yet to be unraveled, however, and the full story of the origin of the Indian Run Formation and the other diamictites in the Potomac Valley will remain enigmatic for the foreseeable.

Annandale Group: Two other metasedimentary rocks—the Lake Barcroft Metasandstone and the Accotink Schist—collectively form the Annandale Group (**Drake and Lyttle, 1981**), which crops out extensively in nearby parts of Fairfax County, but is restricted to a very limited area within the City. The Annandale Group appears to have been the source of the larger sandstone and schist fragments observed in the Indian Run Formation. The Accotink Schist consists of coarse-grained, well-bedded, gray-brown, quartz-mica-garnet schist that crops out in one or more tightly folded bodies in the streambed in Rynex Natural Area, where it is intruded by small bodies of Occoquon Granite. Beds of Lake Barcroft Metasandstone are common in the schist. Contacts with the nearby Indian Run Formation are not exposed, so relations between the two are not known. The schist may represent one or more very large clasts within the diamictite, or it may be preserved in a fold of the main Annandale Group body, which lies just beyond Lake Barcroft northwest of the map area. One body exposed along the west bank of Holmes Run at the mouth of the Rynex ravine forms a narrow screen between bodies of Falls Church Tonalite and Occoquon Granite. In addition to abundant garnet, this body contains small, rectangular masses of white mica that may be replacing the aluminosilicate mineral, *kyanite*.

Figure 3-7 (continued on next page)

Figure 3-7. Lake Barcroft Metasandstone at Greenspring Garden Park. Top: Outcrops of the sandstone are usually marked by well-developed ledges parallel to the bedding; Bottom: Thin interbeds of Accotink Schist (dark gray) are common. Photos by Tony Fleming

The only body of Lake Barcroft Metasandstone within the City even marginally large enough to show on the map is immediately upstream of Shirley Highway, and appears to be a swarm of small to large *xenoliths* of light colored, fine- to medium-grained quartzitic sandstone engulfed by Occoquon Granite. A few thin beds of similar sandstone occur within Accotink Schist in Rynex Natural Area. More extensive exposures of Lake Barcroft Metasandstone can be seen in adjacent parts of Fairfax County, especially along Turkeycock Run in Green Spring Garden Park (fig. 3-7) and on the north side of Lake Barcroft.

Occoquon Granite is the principal *intrusive rock* exposed in the City. It forms the nearly continuous series of scenic, water-sculpted ledges near Beauregard Street, and numerous other outcrops in Holmes Run Valley. Most of the rock consists of well-foliated, light gray, *biotite*-*muscovite* *granite* and *granodiorite* with a distinctive "salt and pepper" appearance (figure 3-8). Many outcrops exhibit two foliations and evidence of multiple generations of folds. Contacts with the adjacent metasedimentary rocks range from sharp to muddled, and are commonly folded. Small dikes and patches of granite are locally abundant in the adjacent wallrocks, but inclusions of wallrocks are sparse and tend to be concentrated near the main contact with the Indian Run Formation. Most outcrops are moderately well jointed; prominent near-horizontal *joints* commonly produce a coarsely slabby or ledge-like appearance in the large outcrops along Holmes Run.

Figure 3-8. Top: Occoquon Granite is readily recognized by its "salt and pepper" texture, produced by grains of dark biotite mica within a light background of quartz and feldspar. Lower left: Sharp contacts (arrows) between coarse-grained biotite granite and finer-grained, grayer Indian Run Formation. Right: Small vein (arrow) of pink-white granite in Indian Run Formation. Dora Kelley Park above Beauregard Street. Photos by Tony Fleming.

The Occoquon Granite occupies a sizable part of southeastern Fairfax and northeastern Prince William Counties—an area sufficiently large to constitute a small *batholith* (**Drake and others, 1979**). The strongly folded northern margin of the batholith runs right through the western part of Alexandria and is responsible for the complex outcrop pattern of granite and metasedimentary rocks in Holmes Run Valley and Rynex. The granite has a high-resolution single-crystal *zircon* age of 472 ± 4 ma (**Aleinikoff and others, 2002**), which is interpreted as the age of crystallization. Within the map area, small dikes and irregular bodies of Occoquon granite visibly intrude the Annandale Group, Indian Run Formation (fig. 3-8), Falls Church Tonalite, and muscovite monzogranite, making it the youngest bedrock unit in Holmes Run Gorge.

Falls Church Tonalite (**Drake and Froelich, 1986**) crops out in a small body along the west bank of Holmes Run, below the outfall of the Rynex ravine. A larger body crops out about a mile upstream in Fairfax County, in the large ravine below Glasgow School and adjacent parts of Holmes Run Gorge below Columbia Pike. The rock consists of medium gray, medium- to coarse-grained *hornblende* *tonalite* that locally contains a sizable number of black inclusions of *mafic* rock. The tonalite in the Rynex exposure is strongly foliated—almost gneissic—and is in contact with a narrow body of Accotink Schist. The tonalite contains several narrow inclusions of schist and sandstone and is itself intruded by small veins of Occoquon Granite. In contrast, the tonalite below Glasgow School is generally more massive looking and has a well-defined igneous flow foliation at many places. The tonalite has been dated at 469±6 ma, which is interpreted as the age of emplacement (**Aleinikoff and others, 2002**).

Figure 3-9. Left: Complicated outcrop at the mouth of Rynex ravine, showing strongly foliated Falls Church Tonalite (T) with inclusions of metasedimentary rocks (M), and cut by irregular veins of pinkish Occoquon Granite (O). Right: Massive Falls Church Tonalite with abundant black hornblende (top), and well foliated, medium grained muscovite monzogranite (bottom), Holmes Run below Glasgow School. Photos by Tony Fleming.

Very light colored muscovite monzogranite (**Drake and Froelich, 1986**) crops out along Holmes Run starting less than 150 feet west of the city limits, and extends upstream along the west bank for almost 3,000 feet. The rock is pinkish-white in color and ranges from sugary textured to coarse grained (figure 3-9). The principal minerals are quartz, *potassium feldspar*, and *muscovite*. Minor amounts of biotite occur in a few exposures. Most of the rock is well foliated and strongly jointed on a small scale, producing abundant rhombic blocks of rock on hillsides. Small bodies of similar rock can be seen cutting the Indian Run Formation at several places along Holmes Run.

Quartz gabbro forms a sizable body on the south side of Lake Barcroft centered on Barcroft Woods, where the rock is well exposed. The gabbro is inferred to hold up several prominent ridges between the lake and Columbia Pike, because their surfaces are characterized by red-brown clayey soil and locally littered with blocks ("float") of weathered gabbro (figure 3-10). Fresh exposures of gabbro are dark greenish black, relatively massive, and composed of stout crystals of *pyroxene*, hornblende, plagioclase, and minor amounts of quartz. Portions of the body are well foliated and metamorphosed to medium-grained *amphibolite*, composed chiefly of hornblende needles and irregular crystals of plagioclase and quartz. A small, lens of soapstone lies along the west edge of the gabbro. It is poorly exposed in a small, mostly water-filled quarry near Jay Miller Drive. The contacts of the gabbro and soapstone with adjacent metasedimentary rocks are not exposed.

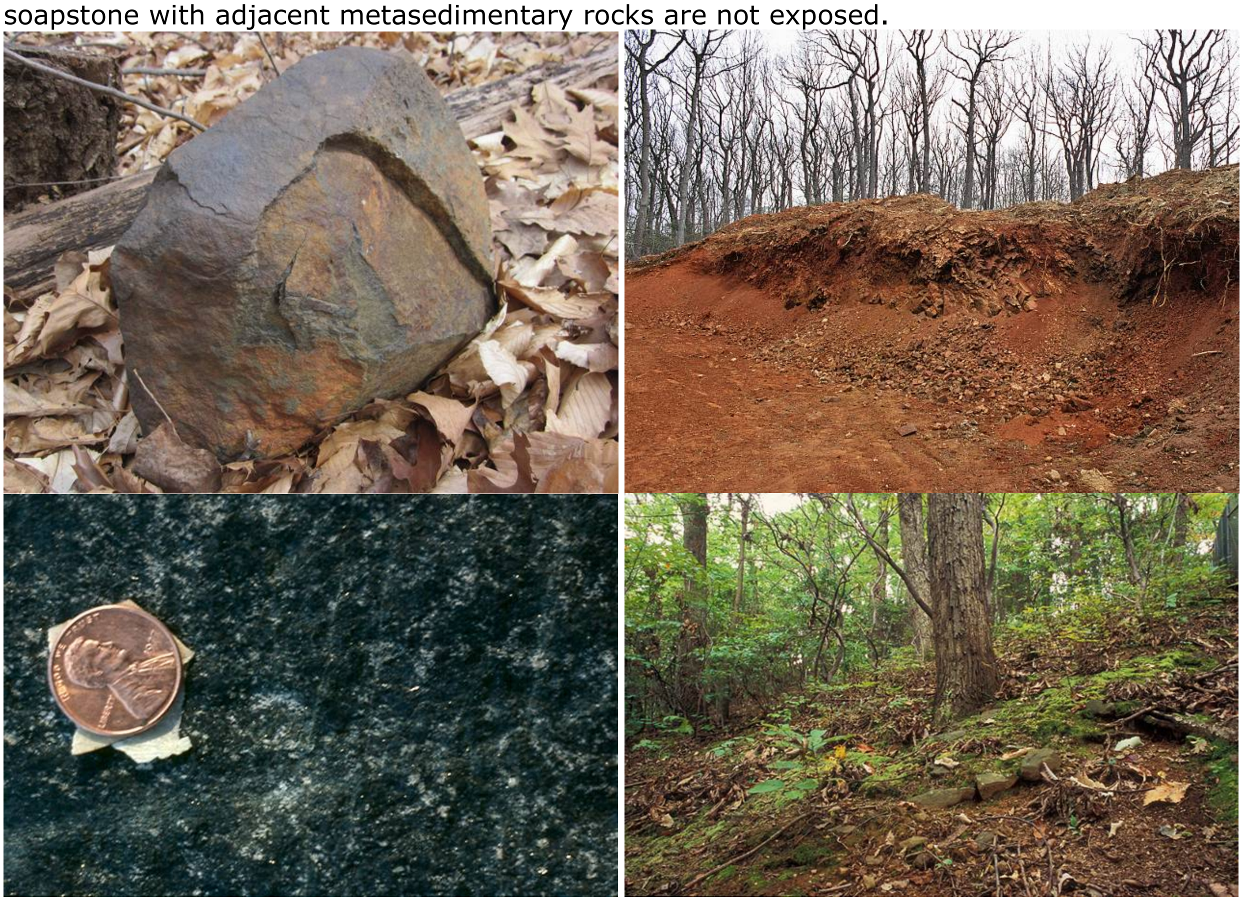

Figure 3-10. Photos of the gabbro body south of Lake Barcroft. Top left: Boulders of gabbro commonly weather to spheroidal shapes. Lower left: Texture of relatively undeformed gabbro. The large black minerals are mostly augite (pyroxene) with rims of hornblende; the light-colored areas are plagioclase and quartz. Top right: The gabbro weathers to a distinctive brownish-red clayey soil with abundant rock fragments. Lower right: Oak-heath forest growing on the ridge in the background of the previous photo. The soil surface is littered with weathered gabbro fragments in a reddish-brown residual soil. Photo credits: Rod Simmons (top left, lower right); Tony Fleming (top right, lower left).

The extent of the gabbro body on plate 3 is much greater than that shown on the Annandale Geologic Map (**Drake and Froelich, 1986**), and more nearly matches the outlines of the body mapped by **Huffman (1975)**. The current map reflects the extent of gabbro outcrops, float, and residual soil observed during this study, the presence of "greenstone" reported by Johnston (**1961**, **1964**) from a water well (#79) near Columbia Pike, as well as certain vegetation patterns. The gabbro weathers to a clayey but fertile soil with high base saturation, leading to a relatively rich flora, especially on moist slopes with north aspects, where basic-mesic Piedmont forest remnants are commonly present. Barcroft Woods, above the Lake Barcroft beach, is a high-quality example of this relationship.

<u>Ages of Intrusive and Metasedimentary Rocks</u>: For decades, determinations of the ages of rock units in and near the map area and elsewhere in northern Virginia were speculative, because of imprecise radiometric dating methods and the scarcity of fossils. More recently, the advent of the sensitive high-resolution ion microprobe (SHRIMP) method has allowed much more precise dating of the radiogenic mineral <u>*zircon*</u> in the intrusive rocks; furthermore, the method can be used not only to date individual zircon crystals, but specific parts of crystals, thereby allowing researchers to distinguish the ages of different thermal events, such as the initial crystallization and emplacement of the rock, versus subsequent metamorphic events that produced overgrowths on the crystals.

SHRIMP ages were determined by **Aleinikoff and others (2002)** for most of the intrusive rocks in the greater Washington, D.C., area, including the Occoquon Granite (472 $\pm$ 4 ma) and Falls Church Tonalite (469$\pm$6 ma) within the area of **plate 3** (table 1).

Table 3-1. Summary of ages and field relations of bedrock map units (ND-not determined).
** present beneath Coastal Plain deposits in the eastern part of the City*

Rock Unit Name	Map Symbol	Zircon Age (ma)	Field Relations	Comments
Mylonite (Rock Creek shear zone)*	RCSZ	ND	Earliest motion at the type locality in Rock Creek Park is coeval with emplacement of the Kensington Tonalite at ~463 ma	Later episodes of motion and faulting are documented from the late Paleozoic through the Cenozoic
Undifferentiated granitic rocks*	Ogu	ND	Unknown-presumed to intrude metasedimentary rocks	Likely to be same or similar age to other intrusive rocks
Occoquon Granite	Oo	472 $\pm$ 4$_{(1)}$	Intrudes Falls Church Tonalite, muscovite monzogranite, and metasedimentary rocks	
Falls Church Tonalite	Of	469 $\pm$ 6$_{(1)}$	Intrudes metasedimentary rocks and muscovite monzogranite	
Gabbro and soapstone	Og-Ou	ND	Contacts not exposed	May be related to and slightly older than the Falls Church Tonalite
Muscovite monzogranite	Om	ND	Intrudes Indian Run Formation	Older than Oo and Of
Chopawamsic Formation*	Oc	470 $\pm$ 2$_{(2)}$ 472 $\pm$ 6$_{(2)}$ 454 $\pm$ 5$_{(3)}$	Intruded by Occoquon Granite in the Occoquon and Fort Belvoir Quadrangles (Seiders and Mixon, 1981)	Probably the volcanic counterpart of the intrusive rocks in the map area
Sykesville Formation*	OCs	ND	Intruded by Falls Church Tonalite and muscovite monzogranite elsewhere in Fairfax County	Identical to the Indian Run Fm. Formed in the same environment at the same time
Indian Run Formation	OCi	ND	Intruded by Occoquon Granite, Falls Church Tonalite, and muscovite monzogranite	Contains fragments of Annandale Group
Annandale Group	OCl-OCa	ND	Intruded by Occoquon Granite and Falls Church Tonalite	Could be significantly older than other rocks

(1) **Aleinikoff and others, 2002**; (2) **Coler and others, 1998**; (3) **Horton and others, 1998**

The ages of these two units compare closely to those for the other intrusive rocks in the D.C. area, and support the concept of a widespread magmatic arc in early to middle Ordovician time (**Aleinikoff and others, 2002**). The SHRIMP ages also are consistent (within the reported error bars) with field relations in Holmes Run Gorge (Table 1), where small bodies of Occoquon Granite appear to intrude Falls Church Tonalite. The zircon age of the muscovite monzogranite was not determined, but it is probably similar to, but somewhat older than, the other intrusive rocks: muscovite monzogranite is intruded by small bodies of Occoquon Granite in Holmes Run Gorge, while **Drake and Froelich (1986)** present evidence that it is intruded by Falls Church Tonalite. The age of the quartz gabbro body near Lake Barcroft also is unknown because no contacts with other intrusive rocks have been observed. In the Georgetown Intrusive Suite in the District of Columbia, however, quartz gabbro is intruded by hornblende-biotite tonalite (**Fleming and others, 1994**); these rocks are virtually identical to gabbro and tonalite of the Falls Church Intrusive Suite, suggesting a similar age relation along Holmes Run.

The metasedimentary rocks are clearly older since they are demonstrably intruded by the intrusive rocks in the map area and elsewhere (figure 3-11). The oldest zircon age limits of the Falls Church Tonalite and Occoquon Granite (~475 ma with the error bars) represent the minimum age limit of the metasedimentary rocks they intrude. The maximum age of the Indian Run Formation is harder to specify, however, **Martin and others (2015)** provide detrital zircon data from the similar and presumably correlative Laurel and Sykesville Formations suggesting that those units were probably deposited between about 550 and 475 ma. Insofar as the Indian Run appears to contain fragments of the Annandale Group, the latter rocks are older than the Indian Run and are tentatively considered to be earliest Ordovician and/or *Cambrian* in age.

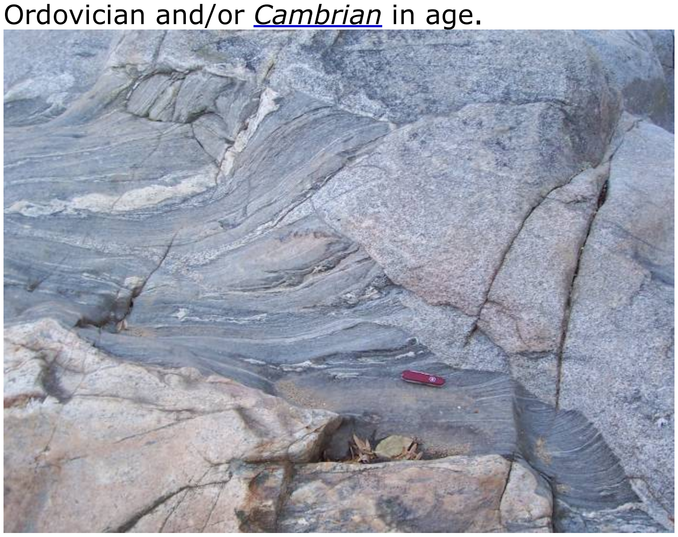

Figure 3-11. Complicated intrusive contact between light pink granite and dark-colored metasedimentary rocks, Four Mile Run, Arlington County. Masses of granite of various sizes are wedging their way into and cross cutting the wallrock. Photo by Tony Fleming.

Structure: At least two fold phases are evident in the rocks exposed in Holmes Run Gorge, and they control the map pattern in that area. The earlier phase consists of open, north-to northeast-trending folds that control the broad outlines of the granite contact. An excellent example can be seen in a set of large outcrops along the west side of Holmes Run at station 146 in Dora Kelley Park (location on **Plate 1**), where an antiformal mass of granite plunges gently northeast, with the metasedimentary wallrocks of the Indian Run arched up over it. At many places, the rocks are refolded about a younger set of tight, *isoclinal folds* that trend north-northwest. A strong, steeply west-dipping cleavage with retrograde mineral assemblages is locally developed parallel to the axial surfaces of the later folds. **Drake and Froelich (1986)** identified several fold generations in the Annandale Quadrangle; the older and younger folds observed in Holmes Run most likely correspond to their Clifton and Accotink folds, respectively. Since both fold phases deform the contacts of the granite, both are synchronous with or younger than the emplacement of the 472 ma Occoquon Batholith.

Figure 3-12. Top left: Dense, fine-grained mylonite derived from granite and Accotink Schist along a fault at the mouth of Rynex ravine. At least two foliations are visible, parallel to the lines (solid line is the youngest). Lower left: Greenish mylonite derived from Falls Church Tonalite, ravine north of Glasgow School. Right: Heavily fractured body of milky-colored vein quartz intruded into the small shear zone exposed in the ravine north of Glasgow School. The host rock is the mylonite in the lower left photo. Photos by Tony Fleming.

A narrow, north-northwest-trending zone of strongly sheared rock is exposed on the west bank of Holmes Run at the mouth of Rynex ravine. This small shear zone offsets the granite contact and appears to mark a small *ductile* fault with dextral displacement. The shear zone is characterized by intensely foliated, gray, fine-grained *mylonite* about 5-10 feet wide. A similar shear zone cuts the Falls Church Tonalite about halfway up the ravine below Glasgow School. The tonalite is sheared into fine-grained, greenish mylonite in the center of the shear zone, which also hosts several irregular bodies of quartz (fig. 3-12). The orientation of the two shear zones is such that they may well represent the same ductile fault because they appear to strike right into each other and have a similar sense of motion.

Bedrock Geology Beneath the Coastal Plain

A large part of the Coastal Plain section of the city appears to be underlain at depth by the Indian Run Formation and Occoquon Granite: the aeromagnetic signatures of these units can be traced from their outcrop in Holmes and Turkeycock Runs to beneath the western and central parts of the city. The contact between them forms a gentle but continuous aeromagnetic gradient (**fig. 3-4**) that runs south from Holmes Run, more or less paralleling South Van Dorn Street across Cameron Valley into southeastern Fairfax County. The gradient separates the distinctive pattern of closed magnetic highs and lows associated with the Indian Run Formation from the monotonous, nearly flat magnetic anomaly of the Occoquon Batholith. A prominent, deep, and roughly equidimensional aeromagnetic low centered on Fort Ward underlies the northern part of the city, and appears to mark a completely buried body of intrusive rock. “Granite” was reported by **Darton (1950)** from an old well near the center of the anomaly. The composition of this body is unknown and is shown as undifferentiated granitoid rocks on **plate 3**. It could be a satellite body of Occoquon Granite, but the deep aeromagnetic low more closely resembles the pattern associated with plutons of Falls Church Tonalite.

The bedrock geology beneath the eastern part of the city, and especially Old Town, appears to differ from the central and western parts. The principal bedrock unit exposed immediately north of the map area in the southern part of the Washington West Quadrangle (**Fleming and others, 1994**) is the Sykesville Formation, which is inferred to extend southward beneath the Coastal Plain in Alexandria. The Sykesville is a diamictite nearly identical to the Indian Run Formation, differing only in small details (fig. 3-13).

Figure 3-13. The Sykesville Formation at Theodore Roosevelt Island (left) and along Donaldson Run in Arlington County (right). The Sykesville and Indian Run Formations are virtually indistinguishable at many places. Compare to figure 3-6. Photos by Tony Fleming.

The relationship between the Sykesville and the Indian Run Formations is speculative. In the Annandale and Falls Church Quadrangles, Drake and Froelich (**1986**; **1997**) interpreted the Sykesville to overlie the Indian Run Formation and Annandale Group on the Burke Thrust Fault. On the other hand, there is no clear field evidence in southern Arlington County that a major fault separates the two formations, and evidence presented elsewhere (e.g., **Hopson, 1964**; **Huffman, 1975**; **Kunk and others, 2005**; **Fleming and Self, 2010**) indicates the two formations are likely one and the same, perhaps being exposed on opposite limbs of a fold, or having been deposited in longitudinally different parts of the same submarine trench or in the same part of the trench at different times. Resolution of this question is well beyond the scope of the present project, and Plate 3 simply shows the inferred boundary between the two units. This speculative boundary follows a moderate to weak, arcuate aeromagnetic gradient that separates the distinctive pattern of closed magnetic highs and lows associated with the Indian Run from the broader magnetic low of the Sykesville as it continues southward from Arlington County, where the unit is well exposed.

The dominant aeromagnetic feature in the eastern section of the city is an intense, quarter- to half-mile-wide, south-to southwest-trending lineament (**fig. 3-4**) that enters the northeastern corner of the map area near National Airport, follows the toe of the Mt Ida escarpment below Del Ray, before crossing Cameron Valley and continuing in the same direction into southeastern Fairfax County beneath the prominent topographic sag occupied by Telegraph Road. This pronounced geophysical anomaly is the southward continuation beneath the coastal plain of the Rock Creek shear zone (RCSZ, **Fleming and Drake, 1998**), a major *fault* zone exposed for many miles in the Washington West and Kensington Quadrangles to the north. Rocks within the RCSZ are sheared into fine-grained ductile *mylonites* that are virtually unrecognizable from their original state (fig. 3-14).

Figure 3-14. Rock Creek Shear Zone, Rock Creek Park, Washington, D.C. Top: Ultramylonite derived from diamictite. The elongate light-colored objects are severely flattened inclusions. Bottom: About 2 feet of <u>fault breccia</u> and <u>gouge</u> (along tree root) separate the walls of this young <u>reverse fault</u> in the middle of the shear zone. Arrows and dashed lines indicate sense of motion and rotation of strata into the fault, respectively. Photos by Tony Fleming.

Structures in the RCSZ reflect a complex, 460-million-year long history of fault motion that began in the Ordovician with major sinistral (left lateral) *strike-slip* displacement, was reactivated later in the Paleozoic by strong oblique dextral (right lateral) slip that included a component of west-side-up reverse faulting. The fault zone was reactivated again in the early Mesozoic by extensional faulting, and then again by post-Cretaceous reverse faulting that has continued sporadically into at least the late Tertiary. Based on visible offset of late Tertiary-Pleistocene(?) stream terraces near the National Zoo in Rock Creek Park, the fault zone is inferred to remain potentially active, though no modern seismicity has been associated with the RCSZ. It may or may not be significant that the aeromagnetic trace of this fault zone beneath Alexandria so closely follows the Mt. Ida escarpment, which separates the central and western highlands of the city from the massive late *Pleistocene* river terrace occupied by Del Ray and Old Town; available data are not sufficiently robust to determine whether there is any tectonic control on the position of the escarpment, but the geographic coincidence is certainly tantalizing. More information on faults and seismic hazards in Alexandria and vicinity appears in **part 8** of the atlas.

The RCSZ forms a major tectonic boundary in Washinton, DC, and the same is inferred to be the case beneath the Alexandria Coastal Plain. The aeromagnetic pattern west of the RCSZ is consistent with the Indian Run and Sykesville Formations, which make up the eastern part of the Potomac terrane (**Horton and others, 1989**). The aeromagnetic pattern east of the shear zone is distinctly different, however, and extends (and expands) southward for some 10-20 miles into the Quantico area (**Bromery and others, 1963**), where fine-grained mafic to felsic metavolcanic rocks of the Chopawamsic Formation are exposed (**Mixon and others, 1972**). **Daniels (1980)** interpreted the pattern east of the RCSZ to represent the Chopawamsic, and reports of "green rock" and "flint" from wells that penetrated bedrock beneath Old Town and Huntington bolster this conclusion. Based on the available data, it appears that the bedrock surface below virtually all of Old Town is composed of metavolcanic rocks of this formation. Like the intrusive rocks in this area, the Chopawamsic is also early to middle Ordovician in age (table 3-1) and probably represents material erupted from the same magmatic arc, transported by strike-slip faulting an unknown distance from its place of origin. In central Virginia, the Chopawamsic and Potomac terranes are separated by a major fault (the Chopawamsic fault); in Alexandria, the RCSZ appears to occupy a similar, terrane-bounding position.

A relatively flat aeromagnetic and gravity anomaly located beneath the river just south of Old Town probably represents a body of granitic rock, perhaps another *pluton* of Occoquon Granite. In a plate tectonics context, the Occoquon Granite, and probably other intrusive rocks in the map area, such as the Falls Church Tonalite, represent so-called "stitching plutons"— bodies of magma intruded across terrane boundaries that essentially weld the terranes together (Horton and others, 1989). The abundance and large volume of intrusive bodies of similar ages in the Potomac terrane of northern Virginia and adjacent areas indicate the region was part of an extensive early to middle Ordovician magmatic arc. These rocks were emplaced over about 35 million years, contemporaneous with the Taconic orogeny as documented in New England (**Aleinikoff and others, 2002**), demonstrating that this event played the major role in assembling and deforming this part of the Piedmont.

Origin and Significance of the Fall Zone
The Fall Zone is the dominant physiographic feature in the City of Alexandria and adjacent parts of Arlington and Fairfax Counties, and is developed along the feather edge of the Coastal Plain sediments as they overlap crystalline bedrock of the Piedmont. The Coastal Plain sediments in this area consist of lower Cretaceous fluvial deposits (Potomac Formation), which form a rapidly east-to-southeast-thickening wedge across Alexandria. These sediments were deposited on a gently eastward-sloping, weathered bedrock surface of low to moderate relief, characterized in places by broad valleys, and elsewhere by more irregular knobs and hills. The change across the Piedmont-Coastal Plain boundary, from

relatively hard, erosion-resistant crystalline rocks to soft and easily eroded unconsolidated sediments, results in a pronounced fall zone along area streams as they cross the boundary in their eastward trip to the Atlantic coast.

The Potomac Formation is thought to have originally extended well west of its present outcrop area (c.f., **Fleming and others, 1994**; **McCartan, 1989**), but gradual tilting of the landscape from west to east has caused the western parts of the unit to be eroded off, and has led to active and ongoing dissection of the bedrock surface outboard of the current Potomac Formation margin, and in the valleys of large trunk streams, such as Four Mile, Holmes, Backlick, and Turkeycock Runs. The modern landscape largely developed during the *Pleistocene*, in response to repeated episodes of continental glaciation that lowered global sea level and caused accelerated downcutting and headward erosion by all of the area streams. A large part of the stream dissection manifested currently by the fall zone represents continuing upstream propagation of pulses of Pleistocene sea level decline and associated stream adjustment to lowered base levels. Holmes Run Gorge is an excellent example of this process. In any event, the configuration of the bedrock surface in areas of active incision, where the Coastal Plain sediments have been stripped off, probably bears little resemblance to the early Cretaceous depositional surface upon which the Potomac Formation was laid down.

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